

**Electromechanical drive or sensor element for a measurement  
instrument, and method for their production**

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The invention relates to an electromechanical drive or a sensor element for a measurement instrument, and a method for their production. It relates in particular to drives and sensor elements manufactured in the form of stacks and composed of piezoelectric elements, and to measurement instruments equipped with such drives and sensor elements.

Known measurement instruments of this type include, for example, piezoelectric acceleration sensors and level measurement instruments. These measurement instruments generally comprise a base body on which the drive or the sensor element is fitted, with these items containing piezoelectric elements, electrodes and electrical connectors and connections. The piezoelectric elements are electrically connected to one another, and are connected to an electronics circuit appropriate to the application.

Such piezoelectric measurement instruments are relatively highly sensitive to electrostatic charges and have relatively low transverse sensitivity. However, their particular disadvantage is their relatively limited effective operating range at high temperatures above, for example, 200°C, under the influence of high static pressures of up to, for example, 500 bar or, in the case of acceleration sensors, when subject to high dynamic loads, during which accelerations of up to 2000 g occur.

The sensitivity of the piezoelectric measurement instruments to the described loads is dependent on the design of their drive or sensor element. Normally, such a drive or such a sensor element is formed from piezoelectric elements which follow one another and are geometrically matched to one another, electrodes as well as electrical

connectors and connections. Various materials, such as piezoceramic and metal, are thus combined with one another and their moduli of elasticity and their respective coefficients of thermal expansion differ. Extended  
5 mechanical planar stresses, which reduce not only the strength of the sensor element but also the wanted signal or measurement signal, are produced in the piezoelectric elements themselves under the influence of the said high temperatures and/or large static and dynamic loads on the  
10 sensor element or on the drive.

In known measurement instruments of the described type, a monolithic thin-film capacitor with a layer structure has also been found to be advantageous, which may also be in  
15 the form of a multiple capacitor composed of thin layers, for example for level measurement instruments. In this case, the layer sequence of the monolith comprises the piezoelectric thin films and electrodes, with electrical connectors being provided, arranged along the monolith.  
20 Normally, a connector (often also referred to as a "rail") then connects the electrodes of the one pole, and another connector connects the electrodes of the other pole. Such a monolithic structure is highly robust, has high strength and allows vibration parameters to be measured very  
25 accurately by reducing the relative coefficients of the transverse transformation.

However, this structure is based on an asymmetric electrode shape, with a projecting part for connection to a rail on  
30 one side and with an isolating clearance from the other rail on the opposite side. Inhomogeneities in the structural design of such drives or sensor elements have a negative effect on the magnitude of the relative transverse transformation coefficient, however. Furthermore, the  
35 asymmetric shape of the electrodes does not allow the entire electrode area of the piezoelectric layers to be charged up, as would be desirable in order to enlarge the transverse transformation coefficient. The smaller the metallization area of the piezoelectric layer under

consideration in comparison with its actual useful area, the greater is the extent to which the transformation coefficient is reduced.

- 5 The invention is thus based on the object of specifying piezoelectric drives and sensor elements, and a method for their production which allow the disadvantages described above to be avoided with measurement instruments equipped in such a way, and which are also distinguished by high  
10 measurement accuracy under the influence of high temperatures, and high static and dynamic loads.

- This object is achieved by a first variant of the invention by means of an electromechanical drive or a sensor element  
15 having a layer structure, which comprises
- a plurality of piezoelectric ceramic layers,
  - an electrode layer which is arranged between two mutually facing surfaces of directly adjacent piezoelectric ceramic layers, and  
20 - an electrical connector for making electrical contact with the electrode layer,
  - in which case the connector is likewise arranged and is passed out between the two mutually facing surfaces of the piezoelectric ceramic layers.

- 25 This object is furthermore achieved by a second variant of the invention by means of an electromechanical drive or sensor element having a layer structure,
- having a plurality of piezoelectric ceramic layers,  
30 - in which mutually facing surfaces of directly adjacent piezoelectric ceramic layers are metallized by application of a metal coating,
  - which are joined together by means of diffusion welding,
  - 35 -- so that an electrode layer is formed by the metallized surfaces,
  - with which contact can be made via an electrical connector.

One preferred embodiment of the invention provides that a groove is provided in at least one of the two mutually facing surfaces of the piezoelectric ceramic layers and at least partially holds the electrical connector.

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In another preferred embodiment of the invention, the connector is a wire which extends beyond the surfaces of the piezoelectric ceramic layers.

- 10 In yet another preferred embodiment of the drive or sensor element according to the invention, at least three piezoelectric ceramic layers and at least two grooves are provided, with these grooves being arranged offset with respect to one another and with respect to a longitudinal axis of the drive or sensor element.
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In a development of a preferred embodiment of the invention, the wire has a rippled or zigzag structure.

- 20 In other developments of the invention, the piezoelectric ceramic layers are composed of PZT material, such as  $\text{PbMg}_{0.308}\text{Nb}_{0.617}\text{Ti}_{0.075}\text{O}_3$ , or they are formed from ceramic layers composed of a material having a Curie temperature of more than  $400^\circ\text{C}$ , for example composed of  $\text{Na}_{0.5}\text{Bi}_{4.5}\text{Ti}_4\text{O}_{15}$  or
- 25  $\text{Bi}_3\text{TiNbO}_9$ .

In other developments of the invention, the electrode layers are composed of a metallic material having a Curie temperature of more than  $400^\circ\text{C}$ , such as bismuth-titanate.

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Other developments, in addition, of the invention relate to wires composed of a metallic material having high-temperature stability at more than  $250^\circ\text{C}$  and wires composed of a material which contains silver and stainless steel, or

35 a material which contains a nickel alloy.

The said object on which the invention is based is, furthermore, achieved by an electromechanical drive or a

sensor element having a layer structure which is produced using a method which comprises the following steps:

- production of ceramic layers composed of electrically active material using a method which is normal in ceramic technology, having desired dimensions and having a margin of 2-3 mm for each dimension taking account of the following mechanical machining;
- 5 - grinding the ceramic layers until a predetermined thickness of, for example, 0.15 to 0.3 mm [sic] is reached;
- 10 - cutting a groove in one face of the ceramic layers which is to be metallized;
- in which case the depth of the groove must be no deeper than half the thickness of the ceramic layer under consideration;
- 15 - coating at least one face of the ceramic layers with metal by applying a paste containing silver twice and subsequent heat treatment at a temperature of 800-820°C;
- 20 - applying adhesive to the metallized surfaces of two ceramic layers using cellulose adhesive;
- diffusion welding of the layers to which adhesive has been applied by heat treatment at a temperature of 780-800°C and single-axis compression at a pressure of 3-5 kg/cm<sup>2</sup> over a period of 3 hours and cooling to room temperature;
- 25 - drawing in each case one connector wire into a groove;
- action of an electric field on the wires at high temperature
- 30 and setting of the desired polarity of the electrode layers by connection of the same poles of the drive or of the sensor element;
- checking of the desired parameters and piezoelectric characteristics of the drive or of the sensor element.
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In addition, a level limit switch is provided which is equipped with a drive and a sensor element according to the invention, with the sensor element in a development of such

a level limit switch being separated from the drive by a non-polarized ceramic layer.

Furthermore, an acceleration sensor is provided, having a  
5 sensor element according to the invention.

The particular advantage is that the construction according to the invention and the production method according to the invention make it possible to produce a piezoelectric drive  
10 or a sensor element in which the charge transformation coefficient and the measurement accuracy of the sensor element are improved in that the relative transverse transformation coefficient is reduced over a wide temperature range and during high static and dynamic loads.

15 The invention will be explained and described in detail in the following text using a number of exemplary embodiments and with reference to a drawing, in which:

20 Figure 1 shows a perspective illustration of a multilayer, previously known piezoelectric drive or sensor element;

25 Figure 2 shows a perspective illustration of a first embodiment of a multilayer piezoelectric drive or sensor element according to the invention;

Figure 3 shows a schematic side view of an upgraded drive or sensor element as shown in Figure 2;

30 Figure 4 shows a schematic illustration of a number of layers of a second embodiment of a piezoelectric drive or sensor element according to the invention;

35 Figure 5 shows schematic side views of two specially shaped wires for a drive or a sensor element according to the invention;

Figure 6 shows a sectional illustration of an acceleration sensor having a multilayer piezoelectric sensor element according to the invention; and

5 Figure 7 shows a schematic, partially cutaway illustration of a level limit switch having a piezoelectric drive and a piezoelectric sensor element according to the invention.

10 In order to make it possible to illustrate the major differences between the invention and the prior art, Figure 1 shows a previously known piezoelectric drive, or a previously known piezoelectric sensor element 1. This will be referred to in the following text, and for the sake of  
15 simplicity, as the piezoelectric element 1. Essentially, it comprises piezoceramic disks 2a, b, c, d, in which at least one of the mutually facing surfaces is metallized and which, with electrodes 3a, b, c inserted in-between, are arranged on top of one another and are joined to one  
20 another in the normal way and so as to produce a structure of a monolithic layer capacitor. Figure 1 also shows a metallic connector 4 which is in the form of a strip, is fitted externally to the outer surface of the piezoelectric element 1 and electrically connects the electrodes 3a and  
25 3c to one another at two connection points 5a and 5b. Another connector of the same type is normally fitted on the other side of the outer surface of the piezoelectric element 1, and is in turn electrically connected to the electrode 3b, although this cannot be seen in Figure 1  
30 owing to the chosen nature of the illustration. Electrical connecting conductors, which are not shown here, can normally be connected to both connectors to form drive or evaluation electronics, which are likewise not shown here for the sake of simplicity.

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In order to prevent the connector 4, which is in the form of a strip, producing an undesired contact with the electrode 3b, it must be cut away at the point where the connector 4 is provided and, so to speak, must be recessed

into the interior of the piezoelectric element 1. It thus cannot cover the entire available area of the disk 2b (or 2c) which, as mentioned initially, has a negative influence on the transformation coefficient at this point on the piezoelectric element 1. The same applies to the electrode 3a, and to the connector which cannot be seen here. It also has to ensure a reasonable separation from the connector, in order to avoid an undesired contact.

Another disadvantage of the known piezoelectric element 1 in Figure 1 has likewise already been mentioned in the introduction. Metallic connectors which are flat or in the form of strips, such as the connector 4, have a thermal expansion behavior at relatively high temperatures which differs significantly from that of the ceramic disks 2a-d. This thermal effect can be of such a magnitude that the connection points 5a, b can be destroyed, thus calling the entire function of the piezoelectric element 1 into question.

A piezoelectric drive or a sensor element 10 as illustrated in Figure 2, which is a first and preferred embodiment of the invention, is more advantageous. The piezoelectric element 10, which is constructed to form a monolithic layer capacitor, in this example comprises four piezoceramic disks 12a, 12b, 12c, 12d into each of which grooves 14a and 14b are cut, as well as grooves 14c and 14d which are arranged offset through approximately 180° with respect to the former. As will be explained later, the grooves 14a-d are cut into the finished, machined ceramic disks 12a-d. That surface of each of the ceramic disks 12a-d which contains the groove 14a-d is metallized over its complete surface together with the disk, as is shown from the example of the layer denoted by 16a. Once the ceramic disks 12a-d have been joined together in the manner shown in Figure 2, preferably by diffusion welding, the metallized layers form electrode layers 16a, 16b, 16c, 16d over the entire surface. The electrode layers 16a and 16c are conductively connected to one another by means of a wire,



which is pulled into the grooves 14a and 14b, as the connector 18a.

5 In this case, undesirable contacts with other electrode  
layers can easily be avoided by the connector projecting  
slightly beyond the outer surface of the piezoelectric  
element 10. Figure 2 shows a connector 18b, which is in the  
form of a wire, connects the electrode layers 16b and 16d,  
and has been pulled into the grooves 14c and 14d in a  
10 similar way to the connector 18a. A further electrical  
connecting conductor for drive or measurement electronics  
can in each case easily be connected to the connectors.

15 It is, of course, not absolutely essential for the  
invention for the connectors 18a and 18b to be arranged in  
the form of the loops shown by way of example in Figure 2.  
It is just as possible for the connectors, which are in the  
form of wires, each to be pulled through the grooves as  
individual sections, that is to say in the sense of  
20 individual wires, and for the individual wires to be  
connected to one another in the desired manner only after  
this has been done. Thus, if desired, each individual  
electrode can in principle be actuated individually. The  
connectors 18a and 18b, which are in the form of wires,  
25 ensure a permanent connection for the electrodes even at  
high temperatures, and allow an electrode layer over the  
complete area.

For strength reasons, it is recommended that the grooves be  
30 cut no deeper into the ceramic layers than half the  
thickness of the respective ceramic disk illustrated by "S"  
in Figure 2. In practice, it has been found to be  
particularly advantageous for the groove depth to  
correspond approximately to 0.3 times the thickness of the  
35 relevant ceramic disk.

The ceramic disks are preferably produced from PZT  
material. The suitability of the piezoelectric element 20  
according to the invention is further improved if the

- ceramic disks are composed of  $\text{PbMg}_{0.308}\text{Nb}_{0.617}\text{Ti}_{0.075}\text{O}_3$ . The piezoelectric ceramic disks are particularly suitable for high temperatures if they are composed of a material having a Curie temperature of more than  $400^\circ\text{C}$ , for example being
- 5 composed of  $\text{Na}_{0.5}\text{Bi}_{1.5}\text{Ti}_4\text{O}_{15}$  or  $\text{Bi}_3\text{TiNbO}_9$ .

- The characteristics of the materials which are used for the electrode layers and for the connectors in the form of wires should be matched to those of the materials used for
- 10 the ceramic disks. It is thus recommended that a metallic material having a Curie temperature of more than  $400^\circ\text{C}$  be used for the electrode layers, preferably a material composed of bismuth-titanate. For the connectors in the form of wires, it has been found to be particularly
- 15 advantageous to use a material having high-temperature stability of more than  $250^\circ\text{C}$ , with preference being given to wires composed of a material containing silver and stainless steel, or a material with a nickel alloy.
- 20 In order to illustrate the versatile options and configurations which result using a piezoelectric element 10 according to the invention, Figure 3 shows a piezoelectric element 10 upgraded such that it is virtually "standing on its head" in comparison with that in Figure 2
- 25 and which now has six ceramic disks 12a, 12b, 12c, 12d, 12e, 12f, five grooves 14a, 14b, 14c, 14d, 14e and, correspondingly, five electrode layers 16b, 16c, 16d, 16e, 16f. As a continuation of the design shown in Figure 2, the connector 18a, which is in the form of a wire, does not
- 30 just run in the grooves 14a, 14b and 14e and thus connects the electrode layers 16a, 16c, 16e to the same polarity, in the same way that the connector 18b, which is in the form of a wire, does for the electrode layers 16b and 16d. Apart from this, what has been said above with regard to the
- 35 piezoelectric element 10 illustrated in Figure 2 also applies here in the same way.

Figure 4 shows a second and preferred embodiment of a piezoelectric drive or sensor element according to the

invention. This sensor element or drive which, for the sake of simplicity, as above, is referred to as the piezoelectric element 20, is illustrated in such a way that the ceramic disks 22a, 22b, 22c, 22d, which are shown  
5 spaced apart from one another, clearly show the profile of the grooves 24a, 24b, 24c, 24d cut into them. In contrast to the grooves 14a-e shown in Figures 2 and 3, the grooves 24a-d do not run through the center of the ceramic disks 22a-d. The grooves 24a-d do not cut a longitudinal axis 29  
10 shown in Figure 4 but run in the general sense of a secant with respect to the circular surfaces, shown by way of example here, of the ceramic disks 22a-d.

Although the position of the grooves 24a-d is intrinsically  
15 arbitrary, they should, however, in a similar way to the grooves 14a-d in Figure 2, once again run such they are arranged offset from one ceramic disk to the other, to be precise preferably in such a way that there is no possibility of any overlap of connectors 28a or 28b,  
20 respectively, arranged in the grooves 24a and 24c, or 24b and 24d, respectively. The distance between the grooves 22a-d and the edge of the ceramic disks 22a-d must be aligned on the basis of the requirements for the mechanical strength of the ceramic disks 22a-d. It has been found that  
25 it is preferable to arrange the grooves half way between the longitudinal axis 29 and the edge of the respective ceramic disk.

The metallized surfaces from which the electrode layers are  
30 formed by joining the ceramic disks 22a-d together (see also Figure 2 and Figure 3 in this context) are denoted by "26a, 26b, 26c, 26d" in Figure 4. Apart from this, what has already been said with regard to the embodiments of the invention illustrated in Figures 2 and 3 applies here.

35 By way of example, Figure 5 shows two different embodiments of the connectors 18a,b and 28a,b (see Figures 2 to 4) which are in the form of wires and which have been found to be particularly advantageous in practice. [lacuna] in that

a [lacuna] and a zigzag connector 32b are advantageous. A connector 32a with a ripple shape and illustrated in Figure 5, as well as a zigzag-shaped connector 32b allows a reliable electrical contact to be made between the electrode layers due to its "ripple peaks" or its zigzags, without the respective elastic characteristics of the said materials being reduced. It is clear that the rippling or zigzagging of the connectors 32a,b which are in the form of wires must be chosen such that this does not make it harder to thread them in the grooves 14a-d or 24a-d (see Figures 2 to 4), respectively.

The electromechanical drives or sensor elements illustrated in Figures 2 to 4 and according to the invention are produced as follows. The method will be explained using the example of the piezoelectric element 10 illustrated in Figure 2. Without any limitation of the invention, the method can also be applied to any other possible electromechanical drives or sensor elements according to the invention.

First of all, the ceramic disks 12a-d are produced from an electrically active material described above using a method which is normal in ceramics technology and having desired dimensions, with a margin of 2-3 mm being provided for each dimension, taking account of the subsequent mechanical machining. The ceramic disks 12a-d are then ground until a predetermined thickness  $s$  of, for example, 0.15 to 0.3 mm is reached. Once the desired groove 14a-d has been ground into each surface of a ceramic disk 12a-d to be metallized, in which case the groove must be no deeper than half the thickness  $S$  of the ceramic layer under consideration, the relevant surface, including the groove, is coated with a metal. This is achieved by applying a paste containing silver at least twice, followed by heat treatment at a temperature of 800-820°C. The ceramic disks are then connected to one another in the desired manner and depending on the desired alignment of the grooves, with two ceramic layers in each case being bonded to one another by

gluing using cellulose adhesive. After this, the ceramic disks which have been joined by adhesive are placed in a suitable frame and are baked to form a monolithic structure with one another by diffusion welding at a temperature of 780-800°C and single-axis compression at a pressure of 3-5 kg/cm<sup>2</sup> over a period of 3 hours, and are then cooled down to room temperature. One connector wire is drawn into each groove, with the electrode layers formed by the metallized layers being polarized in a desired manner by the action of an electric field on the connector wires at high temperature. The electrode layers are then connected to one another in the desired manner. After this, the desired parameters and the piezoelectric characteristics of the drive or of the sensor element are checked.

For the sake of completeness, Figure 6 shows an acceleration sensor 40 which is equipped with a piezoelectric sensor according to the invention. The sensor element 42 comprises ceramic layers 41a, 41b, 41c, 41d, 41e, 41f which are in the form of plates, that is to say they are polygonal, and electrode layers which are arranged between them, which together form a monolithic multilayer capacitor, as already mentioned above. The sensor element 42 is mounted on a baseplate 46 by means of a mounting rod 44. To this end, the individual ceramic plates 41a-f have central openings in a similar way to those in the ceramic disks 22a-d in Figure 4, which together form a central, axial passage through the sensor element 42. The mounting rod 44 is firmly connected to the baseplate 46, runs through the central, axial passage through the sensor element 42, and extends beyond it into a section which is provided with a thread 48. The sensor element 40 is thus placed over the mounting rod 44 and is secured by means of a retaining nut 50, which is screwed to the mounting rod 44, and is mechanically connected to the baseplate 46. Two insulation layers 54a, 54b are used for electrical insulation of the sensor element 40 from the baseplate 46 and from a cover 52, which forms a housing.

The sensor element 40 is essentially constructed in a similar way to the piezoelectric elements 10 and 20 shown in Figures 2 to 4. However, in contrast to them, grooves 56a, 56b, 56c, 56d, 56e, 56f are in this case provided for  
5 holding connectors 58a, 58b in the form of wires, and which grooves run on the outer edges, that is to say on the edges, of the ceramic plates 41a-f. The connectors 58a,b, which are in the form of wires and connect the electrodes of the same polarity in a desired manner, merge into  
10 electrical connecting conductors 60a, 60b, which are combined in a cable 62 which is in turn connected to measurement electronics, which are not shown here.

By way of example, Figure 7 shows a further measurement  
15 instrument, to be more precise a level measurement instrument: a level limit switch 70 which is equipped with a piezoelectric element 72 which is constructed as a monolithic block comprising both a drive and a sensor element according to the invention. The level limit switch  
20 70 comprises a housing 74 and two oscillating rods 76a, 76b attached to it. Such a level limit switch, which has oscillating rods similar to a tuning fork, operates in ways which are generally known and which will thus not be explained any further here.

25 The piezoelectric element 72 is mounted in the interior of the housing 74 by means of a mounting element 78. The housing also holds drive and measurement electronics 80, which are illustrated schematically here.

30 The piezoelectric element 72 is, in principle, once again formed from piezoceramic disks 82a, 82b, 82c, 82d, 82e, 82f and electrode layers which are not identified in any more detail here, in a similar way to the piezoelectric element  
35 shown in Figure 3. The difference in this case is that a sensor element is formed by the ceramic disks 82a, 82b and 82c, and a drive is formed by the ceramic disks 82e and 82f. In order to avoid undesirable stress effects from the

drive element on the sensor element, a non-metallized ceramic disk 82d is provided between them.

5 The piezoelectric element 72 also has two terminating elements 84a, 84b, by means of which it rests on one side against a part of the housing 74 forming a membrane 86, and on the other side against the mounting element 78.

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**Patent Claims**

1. An electromechanical drive or sensor element having a layer structure, which comprises
- 5       - a plurality of piezoelectric ceramic layers (12a-f; 22a-d; 41a-f),
- an electrode layer (16a-e; 26a-d) which is arranged between two mutually facing surfaces of directly adjacent piezoelectric ceramic layers, and
- 10       - an electrical connector (18a,b; 28a,b; 58a,b) for making electrical contact with the electrode layer (16a-e; 26a-d),
- in which case the connector (18a,b; 28a,b; 15       58a,b) is likewise arranged and is passed out between the two mutually facing surfaces of the piezoelectric ceramic layers (12a-f; 22a-d; 41a-f).
- 20   2. An electromechanical drive or sensor element having a layer structure,
- having a plurality of piezoelectric ceramic layers (12a-f; 22a-d; 41a-f),
- in which mutually facing surfaces of directly adjacent piezoelectric ceramic layers (12a-f; 25       22a-d; 41a-f) are metallized by application of a metal coating,
- which are joined together by means of diffusion welding,
- 30       -- so that an electrode layer (16a-e; 26a-d) is formed by the metallized surfaces,
- with which contact can be made via an electrical connector (18a,b; 28a,b; 58a,b).
- 35   3. The drive or sensor element as claimed in one of claims 1 or 2, in which a groove (14a-d; 24a-d; 56a-f) is provided in at least one of the two mutually facing surfaces of the piezoelectric